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Changes in total carbon and nutrients in soil profiles and accumulation in biomass after a 30-year rotation of *Pinus radiata* on podzolized sands: Impacts of intensive harvesting on soil resources

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ABSTRACT

A large proportion of plantations of radiata pine (*Pinus radiata* D. Don) in southern Australia have been established on podzolized coastal sands with low nutrient reserves. Inter-rotational management of the forest floor and harvesting residues has been shown to be critical to maintain the productive capacity of these soils. In 1974 a study was initiated at the end of the first rotation to evaluate the long-term sustainability of fast-growing plantations on these podzolized sands. Growth was measured at 5, 10 and 20 years and prior to clear-felling at age 30. Soil sampling at the end of the first rotation in 1974 was repeated in 2004 prior to clear-felling to determine changes in carbon and nutrients in profiles after 30 years. Forest floor and tree biomass were measured to determine sequestration of carbon and nutrients in mature radiata pine.

Productivity of radiata pine on infertile podzolized sands was either maintained at 26 m^3 ha^{-1} $year^{-1}$ or improved from 21 to 27 m^3 ha^{-1} $year^{-1}$ over two rotations from 1946 to 2005 and this was attributed to conservation of organic matter and nutrients through retention of litter and harvesting residues after the first rotation. Total carbon (23.4 Mg ha^{-1}) and N (595 kg ha^{-1}) remaining in residues and litter after harvesting compensated for losses of carbon (9.2 Mg ha^{-1}) and N (582 kg ha^{-1}) in soil (0–75 cm) over the rotation. Total S, P, K, Ca and Mg remaining on site after conventional harvesting (stem wood and bark) increased during the second rotation (1975–2005). Accumulation of nutrients in the above-ground biomass and soil over 30 years exceeded deposition in rainfall indicating a redistribution of S, P, K, Ca and Mg from the sub-soil to tree biomass. The net accumulation of N in biomass (201 kg ha^{-1}) also exceeded atmospheric deposition indicating significant inputs from nitrogen fixation during the rotation.

Intensive harvesting including removal of log residues and branches for biofuels but leaving foliage on site increased nutrient exports by approximately 30% but did not exceed accession of nutrients over 30 years except for N. In contrast, whole-tree harvesting including foliage increased nutrient exports by 70–150% and fertilizers are likely to be required to compensate for the additional removal of nutrients and to maintain site productivity in the next rotation.

1. Introduction

A large proportion of plantations of radiata pine (*Pinus radiata* D. Don) in southern Australia in excess of 140,000 ha have been established on podzolized sands (Podosols, Haplic Podzols) of low nutrient content. Productivity during the first rotation was relatively high on these infertile coastal sands but growth of the second rotation established after clear-felling and burning residues declined by 25–30% (Keeves, 1966). Subsequently studies showed that inter-rotational management of the forest floor and harvesting residues aimed at conserving organic matter and nutrients was critical to maintain the productive capacity of these soils (Flinn et al., 1979; Farrell, 1984; Squire et al., 1985; Smethurst and Nambiar, 1990a,b). These studies showed that burning of harvesting residues after the first rotation did cause a decline in productivity of the second rotation while retention of residues was shown to maintain or enhance early growth of radiata pine.

Burning after harvesting reduced the mass of residues and litter by 67 Mg ha^{-1} (84%) and losses of N estimated at 220 kg ha^{-1} (72%) were relatively large compared with other nutrients (Flinn et al., 1979). This represented around 28% of total N in the above-ground biomass of a mature radiata pine plantation on podzolized sands. Retention of harvesting residues conserved significant amounts of organic matter and N and increased mineralization of N in litter

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and surface soil for 4 years before returning to levels similar to those of mature radiata pine on the same soil type (Smethurst and Nambiar, 1990a,b). Total amounts of N mineralized during this period ranged between 147 and 211 kg ha^{-1} and a large proportion (80%) of mineral N leached into the sub-soil. Losses of carbon from the surface soil were estimated at 4 Mg ha^{-1} and mixing of residues in the surface soil increased losses to 8 Mg ha^{-1} over 4 years after harvesting (Smethurst and Nambiar, 1990b). The impact of such losses on long-term productivity depends largely on soil reserves and may be detrimental for soils with low organic matter and nutrient content such as these podzolized sands.

Organic matter is the main source of nutrients in podzolized sands (Carlyle, 1993) and therefore maintaining soil carbon is an important factor in the sustainable management of radiata pine plantations on these soils in the coastal regions of southern Australia. More intensive harvesting for conventional timber products and biofuels remove more organic matter and carbon as well as nutrients leaving less for the next rotation (Olsson et al., 1996a,b; Smith et al., 2000; Merino et al., 2005). This is likely to reduce soil quality, lead to long-term depletion of soil resources and have a negative impact on site productivity especially on soils with low nutrient reserves (Fox, 2000). While greater retention of harvesting residues conserves soil organic matter, cultural practices at establishment of the next rotation under these conditions can actually increase losses of carbon and nutrients. For example, soil disturbance and mixing of litter and retained residues in the surface soil together with control of competing vegetation early in the rotation enhanced the decomposition of organic matter and increased the losses of soil carbon (Smethurst and Nambiar, 1990a,b). The recovery of these losses depends largely on the rate of carbon sequestration in plantation biomass and the rotation length and can be enhanced by promoting growth with fertilizers applied during the rotation (Johnson, 1992; Turner et al., 2005).

In 1974 a study was initiated at the end of the first rotation to evaluate the long-term sustainability of fast-growing plantations on these podzolized sands (Squire et al., 1979). It was shown that retention rather than burning residues after harvesting improved survival and early growth of radiata pine on low and high quality sites in response to greater availability of soil moisture and nutrients in particular nitrogen (Squire et al., 1979). Volume growth to age 5, 10 and 20 years was maintained on the high quality site and improved significantly on the low quality site (Squire et al., 1985, 1991, 1996). Results presented here include growth measured at age 30 prior to clear-felling. Tree biomass and litter were measured to determine the sequestration of carbon and nutrients at the end of the rotation. In addition soil profile samples collected in 1974 at the end of the first rotation were collected again to examine changes in carbon and nutrients during the second rotation. The objective of this study was to determine if site productivity and soil resources were maintained during the second rotation of radiata pine and to estimate the impact of harvesting.

2. Methods

2.1. Experimental sites and design

The study sites are located about 25 km from the coast in south-west Victoria (latitude 37°49′ and longitude 140°59′) and average annual rainfall is 767 mm. Soils are podzolized sands derived from Pleistocene aeolian deposits over Miocene limestone and are classed as Podosols based on the Australian soil classification (McKenzie et al., 2004) or Haplic Podzols (IUSS Working Group, 2006).

The first rotation of radiata pine was established after clearing native eucalypt forest and burning harvesting residues prior to planting sites at an average density of 1370 trees ha^{-1} in 1946 (C3) and 1235 trees ha^{-1} in 1949 (C12). No fertilizer was applied during the first rotation and growth of the two stands was classed as low site quality (LQ: C12) and high site quality (HQ: C3) based on stem analysis prior to clear-felling in 1974. Three plots of 0.65 ha each were established in the LQ and HQ stands ($n = 6$) for the comparison of 1R and 2R growth on the same sites. Details of the design and establishment of the experiment are given by Squire et al. (1979).

2.2. Growth

The low site quality stand (LQ) remained unthinned (final density 1153 trees ha^{-1}) during the first rotation and total volume at age 25 years was estimated at 520 m^3 ha^{-1} (mean annual increment: 21 m^3 ha^{-1}). In contrast, the high site quality stand (HQ) was thinned at 17 and 23 years to a final density of 330 trees ha^{-1} and total volume at age 28 years was estimated at 730 m^3 ha^{-1} (mean annual increment: 26 m^3 ha^{-1}) (Squire et al., 1979).

Plots in LQ and HQ stands were harvested late in 1974, residues were retained and the second rotation of radiata pine was planted on the same sites in 1975 at a spacing of 2.4 m × 2.4 m (average density of 1736 trees ha^{-1}) without chemical weed control or fertilizer. Height and diameter were measured frequently to age 5 and again at 10 and 20 years and volume growth during 1R and 2R was compared in detail at each stage of stand development (Squire et al., 1979, 1985, 1991, 1996).

Tree mortality due to infestations of sirex wasp (*Sirex noctilio*) was first noted at age 14 (Squire et al., 1991) and mortality increased to 35% (LQ) and 15% (HQ) by age 20 (Squire et al., 1996); this corresponded to a total volume of dead trees of 136 and 49 m^3 ha^{-1}, respectively. Stands were thinned commercially over a period of 3 years (age 21–23) reducing average density to 328 trees ha^{-1} in LQ and 451 trees ha^{-1} in HQ; total volume of life trees removed at thinning was estimated at 194 and 216 m^3 ha^{-1}, respectively, standing dead trees were felled and left on site.

At the final assessment of the trial in August 2005 height (H in m) and over-bark diameter at 1.3 m (DOB in cm) of trees were measured and total under-bark volume was calculated using the regional volume equation (Vub (m^3) = $9.7 \times 10^{-5} \times \text{DOB}^{1.9} \times H^{0.70}$). In addition, a pre-harvest assessment of merchantable log products using MARVL (Lee and Goulding, 2002) was carried out at each plot to determine the total merchantable yield and log residues for (1) conventional harvesting of saw logs and pulp wood and (2) intensive harvesting including recovery of low grade logs for on-site wood chipping.

2.3. Soils

Soils are podzolized sands with an organic A1 horizon (fine sand) to a depth of 20–30 cm grading to a bleached (albic) A2 horizon (fine sand) to a depth of 130–150 cm over a humic (spodic) Bh horizon (sandy loam) with few coarse fragments of limestone at depth (>200 cm). In 1974 prior to harvesting the 1R stands, soil profile samples were collected from three layers to a depth of 75 cm (layers 0–25, 25–50 and 50–75 cm) for chemical analysis. Profile samples were collected on a grid of 20 sub-plots within each 0.65 ha growth plot and samples from five sub-plots were combined to provide a composite soil sample for each layer (4 composite samples × 3 layers). In addition, soil cores for bulk density measurements (4 cores × 3 layers) were collected from soil pits in two separate plots along opposite boundaries of each growth plot. Soil profile samples for chemical analysis were collected again from the same growth plots in November 2004 at the end of the second rotation (1975–2005) using the original sampling protocol. Bulk density was again measured for each layer